Note: Within nine months of the publication of the mention of the grant of the European patent in the European Patent Bulletin, any person may give notice to the European Patent Office of opposition to that patent, in accordance with the Implementing Regulations. Notice of opposition shall not be deemed to have been filed until the opposition fee has been paid. (Art. 99(1) European Patent Convention).
Description

Background of the Invention

Field of the Invention

[0001] The invention relates generally to the field of transient controlled-source electromagnetic conductivity measurement apparatus and methods subsurface Earth formations. More specifically, the invention relates to methods for acquiring and interpreting controlled-source electromagnetic measurements that account for so-called "run-on" effects. The invention can be used with but is not limited to marine electromagnetic and borehole electromagnetic surveying or geosteering.

Background Art

[0002] Controlled source electromagnetic surveying includes imparting an electric current or a magnetic field into subsurface Earth formations, through the sea floor in marine surveying or through the borehole fluid in borehole surveying, and measuring voltages and/or magnetic fields induced in electrodes, antennas and/or magnetometers disposed near the Earth’s surface or on the sea floor. The voltages and/or magnetic fields are induced in response to the electric current and/or magnetic field imparted into the Earth’s subsurface.


[0004] Following are described several patent publications which describe various aspects of electromagnetic subsurface Earth surveying. For the marine case, U.S. Patent No. 5,770,945 issued to Constable describes a magnetotelluric (MT) system for sea floor petroleum exploration. The disclosed system includes a first water-proof pressure case containing a processor, AC-coupled magnetic field post-amplifiers and electric field amplifiers, a second water-proof pressure case containing an acoustic navigation/release system, four silver-silver chloride electrodes mounted on boats and at least two magnetic induction coil sensors. These elements are mounted together on a plastic and aluminum frame along with flotation devices and an anchor for deployment to the sea floor. The acoustic navigation/release system serves to locate the measurement system by responding to acoustic “pings” generated by a ship-board unit, and receives a release command which initiates detachment from the anchor so that the buoyant package floats to the surface for recovery. The electrodes used to detect the electric field are configured as grounded dipole antennas. Booms by which the electrodes are mounted onto a frame are positioned in an X-shaped configuration to create two orthogonal dipoles. The two orthogonal dipoles are used to measure the complete vector electric field. The magnetic field sensors are multi-turn, Mu-metal core wire coils which detect magnetic fields within the frequency range typically used for land-based MT surveys. The magnetic field coils are encased in waterproof pressure cases and are connected to the logger package by high pressure waterproof cables. The logger unit includes amplifiers for amplifying the signals received from the various sensors, which signals are then provided to the processor which controls timing, logging, storing and power switching operations. Temporary and mass storage is provided within and/or peripherally to the processor.

[0005] U.S. Patent No. 6,603,313 B1 issued to Smnka discloses a method for surface estimation of reservoir properties, in which location of and average earth resistivities above, below, and horizontally adjacent to subsurface geologic formations are first determined using geological and geophysical data in the vicinity of the subsurface geologic formation. Then dimensions and probing frequency for an electromagnetic source are determined to substantially maximize transmitted vertical and horizontal electric currents at the subsurface geologic formation, using the location and the average earth resistivities. Next, the electromagnetic source is activated at or near surface, approximately centered above the subsurface geologic formation and a plurality of components of electromagnetic response is measured with a receiver array. Geometrical and electrical parameter constraints are determined, using the geological and
geophysical data. Finally, the electromagnetic response is processed using the geometrical and electrical parameter constraints to produce inverted vertical and horizontal resistivity depth images. Optionally, the inverted resistivity depth images may be combined with the geological and geophysical data to estimate the reservoir fluid and shaliness properties.

[0006] U.S. Patent No. 6,628,110 B1 issued to Edesmo et al. discloses a method for determining the nature of a subterranean reservoir whose approximate geometry and location are known. The disclosed method includes: applying a time varying electromagnetic field to the strata containing the reservoir; detecting the electromagnetic wave field response; and analyzing the effects on the characteristics of the detected field that have been caused by the reservoir, thereby determining the content of the reservoir, based on the analysis.

[0007] U.S. Patent No. 6,541,975 B2 and U.S. Patent No. 6,670,813 issued to Strack disclose a system for generating an image of an Earth formation surrounding a borehole penetrating the formation. Resistivity of the formation is measured using a DC measurement, and conductivity and resistivity of the formations is measured with a time domain signal or AC measurement. Acoustic velocity of the formation is also measured. The DC resistivity measurement, the conductivity measurement made with a time domain electromagnetic signal, the resistivity measurement made with a time domain electromagnetic signal and the acoustic velocity measurements are combined to generate the image of the Earth formation.

U.S. Patent No. 6,739,165 issued to Strack discloses a method where transient electromagnetic measurement are performed with a receiver or transmitter being placed in a borehole and the other being placed on the surface. Either is being moved and images of fluid content changes of the reservoir are obtained.

[0008] International Patent Application Publication No. WO 0157555 A1 discloses a system for detecting a subterranean reservoir or determining the nature of a subterranean reservoir whose position and geometry is known from previous seismic surveys. An electromagnetic field is applied by a transmitter on the seabed and is detected by antennae also on the seabed. A refracted wave component is sought in the wave field response, to determine the nature of any reservoir present.

[0009] International Patent Application Publication No. WO 03048812 A1 discloses an electromagnetic survey method for surveying an area previously identified as potentially containing a subsea hydrocarbon reservoir. The method includes obtaining first and second survey data sets with an electromagnetic source aligned end-on and broadside relative to the same or different receivers. The invention also relates to planning a survey using this method, and to analysis of survey data taken in combination allowing the galvanic contribution to the signals collected at the receiver to be contrasted with the inductive effects, and the effects of signal attenuation, which are highly dependent on local properties of the rock formation, overlying water and air at the survey area. This is very important to the success of using electromagnetic surveying for identifying hydrocarbon reserves and distinguishing them from other classes of structure.

[0010] U.S. Patent No. 6,842,006 B1 issued to Conti et al. discloses a sea-floor electromagnetic measurement device for obtaining underwater magnetotelluric (MT) measurements of earth formations. The device includes a central structure with arms pivotally attached thereto. The pivoting arms enable easy deployment and storage of the device. Electrodes and magnetometers are attached to each arm for measuring electric and magnetic fields respectively, the magnetometers being distant from the central structure such that magnetic fields present therein are not sensed. A method for undertaking sea floor measurements includes measuring electric fields at a distance from the structure and measuring magnetic fields at the same location.

[0011] U.S. Patent Application Publication No. 2004 232917 relates to a method of mapping subsurface resistivity contrasts by making multichannel transient electromagnetic (MTEM) measurements on or near the Earth’s surface using at least one source, receiving means for measuring the system response and at least one receiver for measuring the resultant earth response. All signals from the or each source-receiver pair are processed to recover the corresponding electromagnetic impulse response of the earth and such impulse responses, or any transformation of such impulse responses, are displayed to create a subsurface representation of resistivity contrasts. The system and method enable subsurface fluid deposits to be located and identified and the movement of such fluids to be monitored.

[0012] U.S. Patent No. 5,467,018 issued to Rueter et al. discloses a bedrock exploration system. The system includes transients generated as sudden changes in a transmission stream, which are transmitted into the Earth’s subsurface by a transmitter. The induced electric currents thus produced are measured by several receiver units. The measured values from the receiver units are passed to a central unit. The measured values obtained from the receiver units are digitized and stored at the measurement points, and the central unit is linked with the measurement points by a telemetry link. By means of the telemetry link, data from the data stores in the receiver units can be successively passed on to the central unit.

[0013] U.S. Patent No. 5,563,913 issued to Tasci et al. discloses a method and apparatus used in providing resistivity measurement data of a sedimentary subsurface. The data are used for developing and mapping an enhanced anomalous resistivity pattern. The enhanced subsurface resistivity pattern is associated with and is an aid for finding oil and/or gas traps at various depths down to a basement of the sedimentary subsurface. The apparatus is disposed on a ground surface and includes an electric generator connected to a transmitter with a length of wire with grounded electrodes. When large amplitude,
long period, square waves of current are sent from a transmission site through the transmitter and wire, secondary eddy currents are induced in the subsurface. The eddy currents induce magnetic field changes in the subsurface which can be measured at the surface of the earth with a magnetometer or induction coil. The magnetic field changes are received and recorded as time varying voltages at each sounding site. Information on resistivity variations of the subsurface formations is deduced from the amplitude and shape of the measured magnetic field signals plotted as a function of time after applying appropriate mathematical equations. The sounding sites are arranged in a plot-like manner to ensure that areal contour maps and cross sections of the resistivity variations of the subsurface formations can be prepared.

[0014] U.S. Patent No. 7,038,456 issued to Ellingsrud et al. discloses an electric dipole transmitter antenna on or close to the sea floor used to induce electromagnetic (EM) fields and currents in the sea water and in the subsurface strata. In the sea water, the EM-fields are strongly attenuated due to the high conductivity in the saline environment, whereas the subsurface strata with less conductivity potentially can act as a guide for the EM-fields due to lower attenuation. If the frequency is low enough (on the order of 1 Hz), the EM-waves are able to penetrate deep into the subsurface, and deeply buried geological layers having higher electrical resistivity than the overburden (as e.g. a hydrocarbon filled reservoir) will affect the EM-waves. Depending on the angle of incidence and state of polarization, an EM wave incident upon a high resistive layer may excite a ducted (guided) wave mode in the layer. The ducted mode is propagated laterally along the layer and leaks energy back to the overburden and receivers positioned on the sea floor. The term "refracted" wave in this specification is intended to refer to this wave mode. Both theory and laboratory experiments show that the ducted mode is excited only for an incident wave with transverse magnetic (TM) polarization (magnetic field perpendicular to the plane of incidence) and at angles of incidence close to the Brewster angle and the critical angle (the angle of total reflection). For transverse electric (TE) polarization (electric field perpendicular to the plane of incidence) the ducted mode will not be excited. Since the induced current is proportional to the electric field, the current will be parallel to the layer interfaces for TE polarization but, for TM polarization, there is an appreciable current across the layer interfaces. A horizontal dipole source on the sea floor will generate both TE and TM waves, but by varying the orientation of the receiver antennae, it is possible to vary the sensitivity to the two modes of polarization. It appears that an in-line orientation (source and receiver dipoles in-line) is more sensitive to the TM mode of polarization, whereas a parallel orientation (source and receiver dipoles in parallel) is more sensitive to the TE mode of polarization. The TM mode is influenced by the presence of buried high resistive layers, whereas the TE mode is not. By measuring with the two antenna configurations and exploiting the difference between the two sets of measurements, it is possible to identify deeply buried high resistivity zones, i.e. a hydrocarbon reservoir.

[0015] U.S. Patent No. 6,717,411 issued to Ellingsrud et al. discloses a method of investigating subterranean strata which includes deploying an electric dipole transmitter antenna, deploying an electric dipole receiver antenna at a predetermined offset distance from the transmitter, applying an electromagnetic (EM) field to the strata using the transmitter, detecting the EM wave field response using the receiver, extracting phase information from the wave response, repeating the procedure with the transmitter and/or receiver in different locations for a plurality of transmissions, and using the phase information from the wave response for the plurality of transmissions in order to determine the presence and/or nature of the reservoir.

[0016] Thus, the offset can be varied by moving the receiver; or indeed the transmitter, or even both. Alternatively, the predetermined offset can be kept constant by moving both the transmitter and receiver. Thus, the horizontal boundaries of the reservoir may be found by analyzing the slope and/or slope change of the curve(s) of phase and/or magnitude as a function of source-receiver offset distance or position, or by analyzing the variation in phase and/or magnitude for a fixed source-receiver offset at several locations. The most useful source-receiver offset is typically larger than the "critical offset". In this part of the curve, the change in slope may indicate the reservoir boundary. Both the source and the receiver are preferably inside the reservoir area to achieve the smallest slope (or gradient). This is true for both the phase and the magnitude curves. Soon after either the source or the receiver leaves the reservoir area, the slopes increases rapidly. From the position where this change occurs, the reservoir boundary may be mapped. The true reservoir boundary will probably lie closer the centre of the reservoir compared to the location where the slope change occurred, typically 10 to 20% of the reservoir depth. The detailed position may be calculated using the measured data and forward modeling.

[0017] A typical f-CSEM marine survey can be described as follows. A recording vessel includes cables which connect to electrodes disposed on the sea floor. An electric power source on the vessel charges the electrodes such that a selected magnitude of current flows through the sea floor and into the Earth formations below the sea floor. At a selected distance ("offset") from the source electrodes, receiver electrodes are disposed on the sea floor and are coupled to a voltage measuring circuit, which may be disposed on the vessel or a different vessel. The voltages imparted into the receiver electrodes are then analyzed to infer the structure and electrical properties of the Earth formations in the subsurface.

[0018] Another technique for electromagnetic surveying of subsurface Earth formations known in the art is transient controlled source electromagnetic surveying (t-
CSEM). In t-CSEM, electric current is imparted into the Earth at the Earth's surface, in a manner similar to f-CSEM. The electric current may be direct current (DC) and slowly varying alternating current (AC) typically in the form of square waves. At a selected time, the electric current is switched off, and induced voltages and/or magnetic fields are measured, typically with respect to time over a selected time interval, at the Earth's surface. Structure of the subsurface is inferred by the time distribution of the induced voltages and/or magnetic fields. t-CSEM techniques are described, for example, in Strack, K.-M., 1992, Exploration with deep transient electromagnetics, Elsevier, 373 pp. (reprinted 1999).

Each of f-CSEM methods and t-CSEM methods has particular advantages and disadvantages in any particular application. Performing both methods sequentially on any particular portion of the Earth's subsurface that is to be surveyed can be time consuming and expensive. Further, it is difficult to obtain both types of surveys on precisely the same portion of the Earth's subsurface when surveys are operated sequentially because of inherent limitations in ability to position the acquisition equipment at precisely the same geodetic positions each time, particularly in the case of marine surveys.

Summary of the Invention

One aspect of the invention is a method for interpreting transient electromagnetic survey data. A method according to this aspect of the invention includes imparting an electromagnetic field in the Earth's subsurface by passing electric current through a transmitter antenna. The electric current includes switched direct current (DC) in the present embodiment, the electrodes can be spaced apart about 50 meters, and can be energized such that about 1000 Amperes of current flows through the electrodes 16A, 16B. The current source (not shown separately) on the vessel 10 is coupled to the electrodes 16A, 16B by a cable 14A. The cable 14A is configured such that the electrodes 16A, 16B can be towed essentially horizontally near the water bottom 13 as shown in Figure 1A. In the present embodiment, the electrodes can be spaced about 50 meters, and can be energized such that about 1000 Amperes of current flows through the electrodes 16A, 16B. This is an equivalent source moment to that generated in typical electromagnetic survey practice known in the art using a 100 meter long transmitter dipole, and using 500 Amperes current. In either case the source moment can be about 5X10^4 Ampere-meters. The electric current used to energize the transmitter electrodes 16A, 16B can include switched direct current (DC). The current may be switched on and off, or, preferably, may be switched to alternate polarity across the electrodes 16A, 16B. As will be further explained, the DC

Detailed Description

Figure 1A shows one embodiment of a marine controlled source electromagnetic (CSEM) survey system for use with methods according to various aspects of the invention. The system includes a survey vessel 10 that moves in a predetermined pattern along the surface of a body of water 11 such as a lake or the ocean. The vessel 10 includes thereon source actuation, recording and navigation equipment, shown generally at 12 and referred to herein as the "recording system." The recording system 12 includes instrumentation to determine the geodetic position of the vessel 10 at any time, such as can be performed using global positioning system (GPS) receivers or the like. The recording system 12 includes equipment to transfer signals from one or more recording buoys 22. The recording buoys 22 receive and store signals from each of a plurality of electromagnetic sensors 20 positioned on the water bottom 13. The sensors 20 may be disposed along a cable 18. The cable 18 may be of a type used in connection with seismic sensors deployed on the water bottom known in the art as "ocean bottom cables."

The sensors 20 detect various electric and/or magnetic fields that result from electric fields induced in the Earth's subsurface by current passing through the electrodes 16A, 16B. The recording buoys 22 may include telemetry devices (not shown separately) to transmit data from the received signals to the vessel 10, and/or may store the signals locally for later interrogation by the recording system 12 or by another interrogation device.

The current source (not shown separately) on the vessel 10 is coupled to the electrodes 16A, 16B by a cable 14A. The cable 14A is configured such that the electrodes 16A, 16B can be towed essentially horizontally near the water bottom 13 as shown in Figure 1A. In the present embodiment, the electrodes can be spaced about 50 meters, and can be energized such that about 1000 Amperes of current flows through the electrodes 16A, 16B. This is an equivalent source moment to that generated in typical electromagnetic survey practice known in the art using a 100 meter long transmitter dipole, and using 500 Amperes current. In either case the source moment can be about 5X10^4 Ampere-meters. The electric current used to energize the transmitter electrodes 16A, 16B can include switched direct current (DC). The current may be switched on and off, or, preferably, may be switched to alternate polarity across the electrodes 16A, 16B. As will be further explained, the DC

Figure 1A shows one embodiment of a marine controlled source electromagnetic (CSEM) survey system for use with methods according to various aspects of the invention. The system includes a survey vessel 10 that moves in a predetermined pattern along the surface of a body of water 11 such as a lake or the ocean. The vessel 10 includes thereon source actuation, recording and navigation equipment, shown generally at 12 and referred to herein as the "recording system." The recording system 12 includes instrumentation to determine the geodetic position of the vessel 10 at any time, such as can be performed using global positioning system (GPS) receivers or the like. The recording system 12 includes equipment to transfer signals from one or more recording buoys 22. The recording buoys 22 receive and store signals from each of a plurality of electromagnetic sensors 20 positioned on the water bottom 13. The sensors 20 may be disposed along a cable 18. The cable 18 may be of a type used in connection with seismic sensors deployed on the water bottom known in the art as "ocean bottom cables."

The sensors 20 detect various electric and/or magnetic fields that result from electric fields induced in the Earth's subsurface by current passing through the electrodes 16A, 16B. The recording buoys 22 may include telemetry devices (not shown separately) to transmit data from the received signals to the vessel 10, and/or may store the signals locally for later interrogation by the recording system 12 or by another interrogation device. The current source (not shown separately) on the vessel 10 is coupled to the electrodes 16A, 16B by a cable 14A. The cable 14A is configured such that the electrodes 16A, 16B can be towed essentially horizontally near the water bottom 13 as shown in Figure 1A. In the present embodiment, the electrodes can be spaced about 50 meters, and can be energized such that about 1000 Amperes of current flows through the electrodes 16A, 16B. This is an equivalent source moment to that generated in typical electromagnetic survey practice known in the art using a 100 meter long transmitter dipole, and using 500 Amperes current. In either case the source moment can be about 5X10^4 Ampere-meters. The electric current used to energize the transmitter electrodes 16A, 16B can include switched direct current (DC). The current may be switched on and off, or, preferably, may be switched to alternate polarity across the electrodes 16A, 16B. As will be further explained, the DC

Brief Description of the Drawings

Figure 1A shows a marine electromagnetic survey system using a horizontal electric dipole current source and a seismic source.

Figure 1B shows a marine electromagnetic survey system using a vertical electric dipole current source.

Figure 2 shows an alternative way to energize the Earth using magnetic fields.

Figure 3 shows one embodiment of an electromagnetic sensor.

Figure 4 shows the current waveform used for a combination time and frequency domain excitation in one embodiment of a method according to the invention.
used to energize the electrodes 16A, 16B may be switched so as to have a switching frequency on the order of 0.01 to 1 Hz.

[0031] The vessel may also tow a seismic source 9 for contemporaneous seismic and electromagnetic surveying. In such embodiments, the water bottom cable 18 may include seismic sensors 21 of any type known in the art.

[0032] In the present embodiment, as the current through the transmitter electrodes 16A, 16B is switched, a time-indexed recording of electric and/or magnetic fields detected by the various sensors 20 is recorded, either in the recording buoys 22 and/or in the recording system 12, depending on the particular configuration of recording and/or telemetry equipment in the recording buoys 22 and in the recording system 12. The time indexed recording is indexed to the time at which the current is switched, so as to record transient electromagnetic response of the subsurface Earth formations 15, 17. In addition, a recording of the signals detected by the various sensors 20 is made over a length of time intended to include a selected number of switching events, typically on the order of 1,000 to 2,000 switching events. Such recordings will include signals having characteristics related to the frequency domain response of the surface Earth formations to the electromagnetic fields induced by the switched DC imparted to the electrodes 16A, 16B. As will be readily appreciated by those skilled in the art, such response will include equivalent responses to the fundamental switching frequency, which is as explained above preferably on the order of 0.01 to 1 Hz, and odd harmonics thereof.

[0033] Figure 1B shows an alternative implementation of signal generation and recording, in which the transmitter electrodes 16A, 16B are arranged such that they are oriented substantially vertically along a cable 14B configured to cause the electrodes 16A, 16B to be oriented substantially vertically as shown in Figure 1B. Energizing the electrodes 16A, 16B, detecting and recording signals is performed substantially as explained above with reference to Figure 1A.

[0034] The embodiments of Figure 1A and Figure 1B use electric current applied to electrodes to impart an electric field into the Earth’s subsurface. An alternative to electric fields is to use magnetic fields, and such will be explained with reference to Figure 2. In Figure 2, the vessel 10 tows a cable 14C which is connected to two loop transmitters 17A and 17B. The first loop transmitter 17A encloses and area perpendicular to the water bottom 13. Periodically, the recording system 12 causes electric current to flow through the first loop transmitter 17A. The current can be in any of the same forms as described with reference to Figure 1A, including switched DC, PRBS, and alternating polarity DC. When the current changes, a transient magnetic field having dipole moment along direction M₀ is imparted into the Earth. At the same or at different times, current is applied to the second loop transmitter 17B. The second loop transmitter may be in the form of a solenoid coil, having a magnetic moment along direction M₁.

[0035] The foregoing embodiments have been explained in the context of marine electromagnetic surveying. It should be clearly understood that the foregoing embodiments are equally applicable to surveys conducted on land at the surface of the Earth.

Figure 3 shows one embodiment of a sensor 20 in more detail. The sensor 20 may be enclosed in a housing 23 made from a dense, electrically non conductive, non magnetic material such as high density plastic such that the sensor 20 will sink in the water and rest on the water bottom (13 in Figure 1A). Electrodes 26A, 26B, 28A, 28B are positioned on the bottom of the housing 23 such that they contact the water bottom (13 in Figure 1A). The electrodes are arranged in dipole pairs. One pair 26A, 26B can be oriented along the length of cable (18 in Figure 2A), and measures voltages along the direction of the cable. The other electrode pair 28A, 28B can be oriented transversely to the cable (18 in Figure 2A) and measures voltages induced transversely to the cable (18 in Figure 2A). The electrode pairs may span a distance of about 1 to 10 meters. The electrode pairs 26A, 26B and 28A, 28B may be coupled to a combined amplifier/digital signal processor 24 for converting the detected voltages into digital words corresponding to the voltage amplitude at selected moments in time. The present embodiment of the sensor 20 may include one or more magnetometers 30, 32, 34 oriented along mutually orthogonal directions. In the present embodiment, two of the magnetometers 30, 32 may be oriented such that their sensitive axes are oriented along the same direction as the dipole moment of a corresponding electrode pair 26A, 26B and 28A, 28B. The signal output of each magnetometer 30, 32, 34 may be coupled to the digital signal processor 24. The digitized signal output of the signal processor 24 can be coupled to the recording buoy (22 in Figure 2A) for transmission to the recording system (12 in Figure 1A) or later interrogation by the recording system (12 in Figure 1A).

[0037] Figure 4 shows a graph of a simulation of electric current passed through a transmitter antenna (as explained above either coils or electrodes) in the upper graph at curve 40, and voltages induced in a receiver antenna (also as explained above either coils, magnetic field detectors or electrodes) in the lower graph at curve 49. The transmitter current may be switched, at negative-going switching events 44A, and at positive-going switching events 44B. The switching events 44A, 44B may cause the current to vary a substantially equal amount above, and correspondingly below, a reference current level, which may be zero or other value. A time duration between successive corresponding polarity switching events (negative-going 44A or positive-going 44B) is referred to as the "base period" and is inversely related to a base frequency of equivalent alternating current. Transient response in the induced voltages is visible after each current switching event, as shown at 48 for nega-
tive-going switching events and at 50 for positive-going switching events. In a method according to the invention, transient electromagnetic response of the water and the subsurface formations (15, 17 in Figure 1A) may be determined, for example, using a method described in U.S. Patent Application Publication No. 20060186887 filed by Strack et al. and incorporated herein by reference. Such method uses the transient response 48, 50 from at least one switching event to determine spatial distribution of conductivity in the Earth’s subsurface.

[0038] The switched current passing through the transmitter antenna will also introduce frequency domain electromagnetic effects in the water and in the Earth’s subsurface. The effective frequency content of such effects will be related to the switching frequency (base period) and harmonics thereof. In a method according to the invention, frequency domain response of the Earth’s subsurface may be interpreted to determine the presence of subsurface resistive features, such as hydrocarbon reservoirs, using an interpretation technique described, or examiner, in U.S. Patent No. 7,038,456 issued to Ellingsrud et al. and incorporated herein by reference. In one embodiment, the response of the water may be determined such as described in the Strack et al. ‘887 publication cited above using the transient response of the Earth measured at one or more switching events. Such water response may be attenuated from, deconvolved from or otherwise subtracted form the frequency domain response determined or just used as explained above. The result can be a model of the spatial distribution of the resistivity in the Earth’s subsurface substantially corrected for the effects of the body of water above the subsurface formations.

[0039] It will be appreciated by those skilled in the art that if the switching frequency is sufficiently high, and the base period is then relatively short, that so-called “run-on” may affect the quality of transient electromagnetic measurements made after one or more switching events. Run-on refers to residual transient effects from one switching event affecting subsequent transient measurements because the prior transient effects have not sufficiently decayed. Run-on generally increases in effect as the switching frequency increases. One embodiment of an acquisition and processing method according to the invention that is intended to deal with the run-on effect is shown in the form of a flow chart in Figure 5. Transient electromagnetic data may be acquired substantially as explained above with reference to FIGS. 1A, 1B and 2. At 60, an initial model of the conductivity distribution in the Earth’s subsurface is made for a volume of the Earth’s subsurface, typically that corresponds to the acquisition geometry at the time the CSEM measurements are made. The volume will depend on, among other factors, the positions of the various electrodes and/or loop antennas used during measurement acquisition. The initial model is used, at 62, to generate an expected transient response (whether in voltage or magnetic field amplitude) with respect to time for a first selected switching event.

As previously explained, such switching event may be current switch on, current switch off or current polarity reversal. Current polarity reversal, in some embodiments, may include a short duration intervening current switch off, depending on the apparatus used to make the measurements. It will be appreciated by those skilled in the art that forward modeling programs known in the art for calculating transient response do not take account of any undecayed effects of prior current switching events.

[0040] In the present embodiment, at 64, a transient response for a switching event prior in time to the first switching event in the acquisition sequence is calculated, preferably using the same forward modeling procedure used to calculate the transient response for the first switching event, and using the same initial model of conductivity distribution. At 66, the calculated transient response of the prior switching event is evaluated with respect to a selected threshold. The selected threshold may be, for example, a predetermined fraction of the peak amplitude of the transient response of the first switching event. The selected threshold may be a predetermined peak amplitude value. If the peak amplitude of the calculated response of the prior switching event is below the threshold, at 70, the calculated responses of the prior event and the first switching event are summed. The threshold is selected such that the effect of a switching event having such transient response is believed to substantially not affect the measured response of the first switching event.

[0041] If the calculated response for the prior event is above the selected threshold, then at 68 the data are examined for a switching event back in time from the prior switching event. A transient response for such back in time switching event is calculated at 34, just as for the prior switching event. The foregoing process is repeated for successively earlier switching events until the peak amplitude of the calculated transient response for such switching event is below the selected threshold. At such time, the calculated transient responses for all such switching events are summed, at 70. The summed response is compared, at 71, to the voltage and/or magnetic field actually measured at the first switching event. At 72, if the difference between the summed calculated responses and the measured response exceeds a selected threshold, at least one parameter of the initial model is adjusted, at 66, and the process is repeated from 62 to 72. Such adjustment of the model, and repetition of the process continues until the difference between the calculated response and the measured response is below the selected threshold, at 74, at which point the process is completed with respect to the first switching event.

[0042] The foregoing procedure may be repeated for measurements corresponding to other volumes in the Earth’s subsurface until the user has determined conductivity distribution over a desired total volume of the Earth’s subsurface.

[0043] Alternatively, the measurements made are analyzed without reference to a model of the Earth’s sub-
surface. In such alternative implementation, transient response of some portion of the Earth's subsurface or other medium is measured during a plurality of switching events. The response will include decaying amplitude of measured induced voltage and/or magnetic field. The transient response after a first one of the switching events may then be modeled such as by curve fit or other mathematical representation, or by equivalent analog circuit analysis, for example. In the present embodiment, at 64, a transient response for a switching event prior in time to the first switching event in the acquisition sequence is calculated, preferably using the same modeling procedure used to calculate the transient response for the first switching event. At 66, the calculated transient response of the prior switching event is evaluated with respect to a selected threshold. The selected threshold may be, for example, a predetermined fraction of the peak amplitude of the transient response of the first switching event. The selected threshold may be a predetermined peak amplitude value. If the peak amplitude of the calculated response of the prior switching event is below the threshold, at 70, the calculated responses of the prior event and the first switching event are summed. The threshold is selected such that the effect of a switching event having such transient response is believed to substantially not affect the measured response of the first switching event.

If the calculated response for the prior switching event is above the selected threshold, then at 68 the data are examined for a switching event back in time from the prior switching event. A transient response for such back in time switching event is calculated at 64, just as for the prior switching event. The foregoing process can be repeated for successively earlier switching events until the peak amplitude of the calculated transient response for such switching event is below the selected threshold. At such time, the calculated transient responses for all such switching events are summed, at 70. The summed response is compared, at 71, to the voltage and/or magnetic field actually measured at the first switching event. At 72, if the difference between the summed calculated responses and the measured response exceeds a selected threshold, at least one parameter of the model is adjusted, at 66, and the process is repeated from 62 to 72. Such adjustment of the model, and repetition of the process continues until the difference between the calculated response and the measured response is below the selected threshold, at 64, at which point the process is completed with respect to the first switching event.

Embodiments of a method according to the various aspects of the invention may provide better interpretation of the resistivity distribution in surveyed areas of the Earth's subsurface, while keeping data acquisition time to a minimum.

While the invention has been described with respect to a limited number of embodiments, those skilled in the art, having benefit of this disclosure, will appreciate that other embodiments can be devised which do not depart from the scope of the invention as disclosed here-in. Accordingly, the scope of the invention should be limited only by the attached claims.

Claims

1. A method for interpreting transient electromagnetic survey data, comprising:

   - imparting an electromagnetic field in the Earth’s subsurface by passing electric current through a transmitter antenna (16A, 16B ; 17A, 17B), the electric current comprising switched direct current at a selected switching frequency;
   - detecting voltages induced in a receiver (20, 21) corresponding to electromagnetic effects induced in the Earth’s subsurface; said method being characterized in that it comprises:
   - determining frequency domain electromagnetic response of the Earth’s subsurface from the detected voltages; and
   - determining transient electromagnetic response of the Earth’s subsurface from the detected voltages;

   wherein the frequency domain electromagnetic response and the transient electromagnetic response are determined from the same detected voltages;

   wherein the frequency domain electromagnetic response is determined from a portion of the induced voltages detected over a plurality of cycles of the current switching; and

   wherein the transient electromagnetic response is determined from a portion of the induced voltages detected within a time duration after one or more current switching events, said time duration being a time period in which an amplitude of the induced voltages is decaying.

2. The method of claim 1 wherein the electric current is switched to exceed and fall substantially a same amount respectively above and below a reference value.

3. The method of claim 2 wherein the reference value is substantially zero.

4. The method of any one of claims 1 to 3 wherein the transmitter antenna comprises a dipole electrode (16A, 16B).

5. The method of any one of claims 1 to 3 wherein the transmitter antenna comprises a wire loop (17A, 17B).
6. The method of any one of claims 1 to 3 wherein the receiver comprises a dipole electrode (26A, 26B; 28A, 28B).

7. The method of any one of claims 1 to 3 wherein the receiver comprises a wire loop.

8. The method of any one of claims 1 to 3 wherein the receiver comprises a magnetometer (30, 32, 34).

9. The method of any one of claims 1 to 3 wherein at least one of the imparting an electromagnetic field and the detecting is performed so as to have magnetic dipole moment (m_A) substantially vertical.

10. The method of any one of claims 1 to 3 or 9 wherein at least one of the imparting an electromagnetic field and the detecting is performed so as to have magnetic dipole moment (m_B) substantially horizontal.

11. The method of any one of claims 1 to 10 wherein the determining frequency domain electromagnetic response comprises measuring a characteristic of the detected voltages over a plurality of cycles of the current switching.

Patentansprüche

1. Verfahren zum Interpretieren transienten elektromagnetischer Erhebungsdaten umfassend:

Übertragen eines elektromagnetischen Feldes im Erduntergrund mittels Durchleiten elektrischen Stroms durch eine Transmitterantenne (16A, 16B; 17A, 17B), wobei der elektrische Strom geschaltetem Gleichstrom bei einer ausgewählten Schaltfrequenz umfasst;

Detektieren von in einem Empfänger (20, 21) induzierbaren Spannungen, die im Erduntergrund induzierten elektromagnetischen Effekten entsprechen,

wobei das Verfahren dadurch gekennzeichnet ist, dass es umfasst:

Bestimmen der elektromagnetischen Frequenzbereichsantwort des Erduntergrundes aus den detektierten Spannungen, und

Bestimmen der transiente elektromagnetischen Antwort des Erduntergrundes aus den detektierten Spannungen, wobei die elektromagnetische Frequenzbereichantwort und die transiente elektromagnetische Antwort aus denselben detektierten Spannungen bestimmt werden, wobei die elektromagnetische Frequenzbereichantwort aus einem Teil der über mehrere Stromschaltzyklen detektierten induzierten Spannungen bestimmt wird, und wobei die transiente elektromagnetische Antwort aus einem Teil der innerhalb einer Zeitdauer nach einem oder mehreren Schaltvorgängen detektierten induzierten Spannungen bestimmt wird, wobei die Zeitdauer eine Zeitspanne ist, in der eine Amplitude der induzierten Spannungen abklingt.

2. Verfahren nach Anspruch 1, wobei der elektrische Strom so geschaltet wird, dass er einen Referenzwert im Wesentlichen in gleichen Maß übersteigt und unter diesen fällt.

3. Verfahren nach Anspruch 2, wobei der Referenzwert im Wesentlichen null ist.

4. Verfahren nach einem der Ansprüche 1 bis 3, wobei die Transmitterantenne eine Dipolelektrode (16A, 16B) umfasst.

5. Verfahren nach einem der Ansprüche 1 bis 3, wobei die Transmitterantenne eine Drahtschleife (17A, 17B) umfasst.


7. Verfahren nach einem der Ansprüche 1 bis 3, wobei der Empfänger eine Drahtschleife umfasst.

8. Verfahren nach einem der Ansprüche 1 bis 3, wobei der Empfänger ein Magnetometer (30, 32, 34) umfasst.

9. Verfahren nach einem der Ansprüche 1 bis 3, wobei wenigstens eines von Übertragen eines elektromagnetischen Feldes und Detektieren so durchgeführt wird, dass ein im Wesentlichen vertikales magnetisches Dipolmoment (m_A) erhalten wird.

10. Verfahren nach einem der Ansprüche 1 bis 3 oder 9, wobei wenigstens eines von Übertragen eines elektromagnetischen Feldes und Detektieren so durchgeführt wird, dass ein im Wesentlichen horizontales magnetisches Dipolmoment (m_B) erhalten wird.

11. Verfahren nach einem der Ansprüche 1 bis 10, wobei das Bestimmen der elektromagnetischen Frequenzbereichsantwort Messen einer Eigenschaft der detektierten Spannungen über mehrere Stromschaltzyklen umfasst.

Revendications

1. Procédé d’interprétation de données de levés électromagnétiques transitoires, comprenant :
l’application d’un champ électromagnétique dans la subsurface terrestre en faisant passer un courant électrique à travers une antenne émettrice (16A, 16B ; 17A, 17b), le courant électrique comprenant un courant continu commuté à une fréquence de commutation sélectionnée ; la détection des tensions induites dans un récepteur (20, 21) correspondant à des effets électromagnétiques induits dans la subsurface terrestre ;

ledit procédé étant caractérisé en ce qu’il comprend :

la détermination d’une réponse électromagnétique dans le domaine fréquentiel de la subsurface terrestre, à partir des tensions détectées ; et

la détermination d’une réponse électromagnétique transitoire de la subsurface terrestre à partir des tensions détectées ;

10 dans lequel la réponse électromagnétique dans le domaine fréquentiel et la réponse électromagnétique transitoire sont déterminées à partir des mêmes tensions détectées ;

20 dans lequel la réponse électromagnétique dans le domaine fréquentiel est déterminée à partir d’une partie des tensions induites détectées sur une pluralité de cycles de la commutation de courant ; et

30 dans lequel la réponse électromagnétique transitoire est déterminée à partir d’une partie des tensions induites détectées pendant un certain laps de temps après un ou plusieurs événements de commutation de courant, ledit laps de temps étant une période de temps pendant laquelle une amplitude des tensions induites décroît.

2. Procédé selon la revendication 1, dans lequel le courant électrique est commuté de façon à monter et descendre, essentiellement d’une même quantité, respectivement au-dessus et en dessous d’une valeur de référence.

3. Procédé selon la revendication 2, dans lequel la valeur de référence est essentiellement zéro.

4. Procédé selon l’une quelconque des revendications 1 à 3, dans lequel l’antenne émettrice comprend une électrode dipôle (16A, 16B).

5. Procédé selon l’une quelconque des revendications 1 à 3, dans lequel l’antenne émettrice comprend une boucle de fil métallique (17A, 17B).


7. Procédé selon l’une quelconque des revendications 1 à 3, dans lequel le récepteur comprend une boucle de fil métallique.

8. Procédé selon l’une quelconque des revendications 1 à 3, dans lequel le récepteur comprend un magnétomètre (30, 32, 34).

9. Procédé selon l’une quelconque des revendications 1 à 3, dans lequel au moins l’une de l’application d’un champ électromagnétique et de la détection est effectuée de façon à avoir un moment dipolaire magnétique (mₐ) essentiellement vertical.

10. Procédé selon l’une quelconque des revendications 1 à 3 ou 9, dans lequel au moins l’une de l’application d’un champ électromagnétique et de la détection est effectuée de façon à avoir un moment dipolaire magnétique (mₐ) essentiellement horizontal.

11. Procédé selon l’une quelconque des revendications 1 à 10, dans lequel la détermination de la réponse électromagnétique dans le domaine fréquentiel comprend la mesure d’une caractéristique des tensions détectées sur une pluralité de cycles de la commutation de courant.
FIG. 4

BASE PERIOD 47

ON +

44A

44B

ON -

46

47

ON +

44A

44B

ON -

46

50

50

50

TRANSMITTER CURRENT (A)

RECEIVER VOLTAGE (V)

48
REFERENCES CITED IN THE DESCRIPTION

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